THE FIRST LAW APPLIED IN THERMODYNAMIC SYSTEMS

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First Law in an Open or Steady-Flow System:

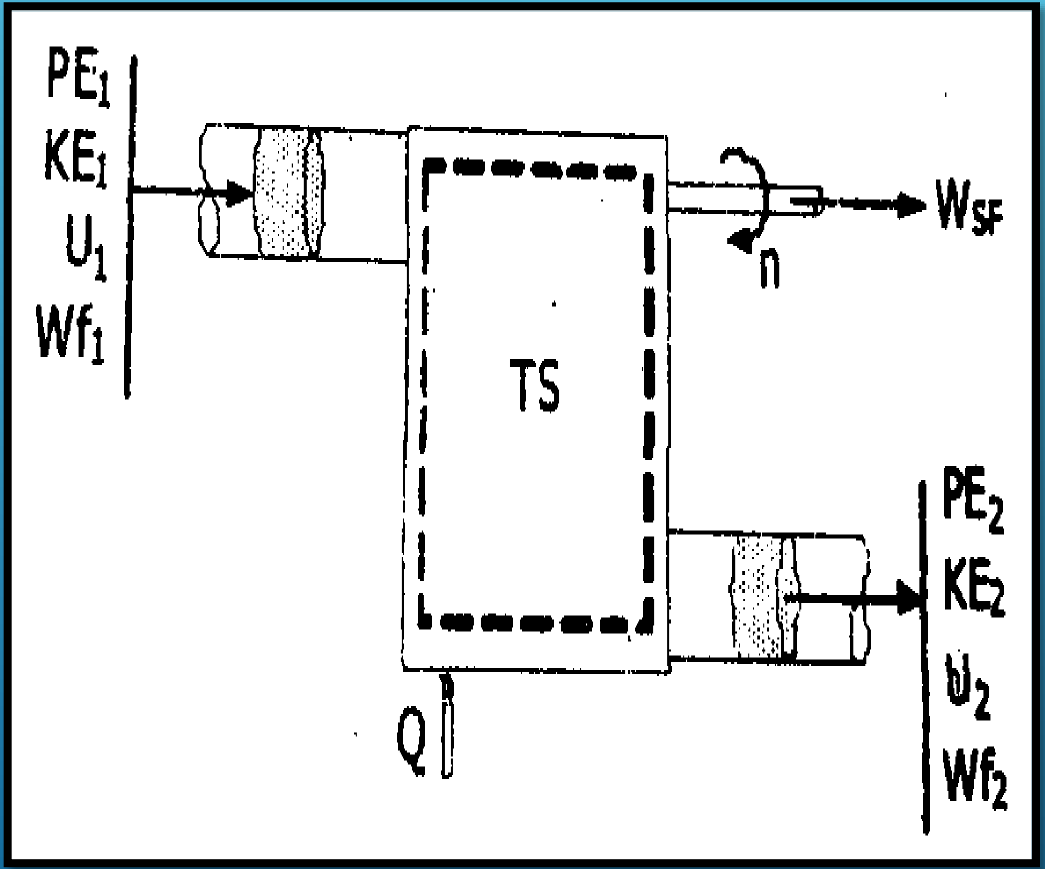


FIGURE: Energy balance in an open or steady-flow thermodynamic system

$$[E_{IN} = E_{OUT}]$$

$$PE_1 + KE_1 + U_1 + W_{f_1} + Q = W_{SF} + PE_2 + KE_2 + U_2 + W_{f_2}$$

$$Q = W_{SF} + \Delta PE + \Delta KE + \Delta U + \Delta W_f;$$

When:

$$\Delta PE \approx 0;\ Z_1 \approx Z_2$$

$$\Delta KE \approx 0;\ V_1 \approx V_2$$

And:

$$\Delta H = \Delta U + \Delta W_f$$

$$\boxed{Q = W_{SF} + \Delta H}$$ Steady-Flow Energy Equation (SFEE)

In differential form:

$$dQ = dW_{SF} + dH$$

General Formula:

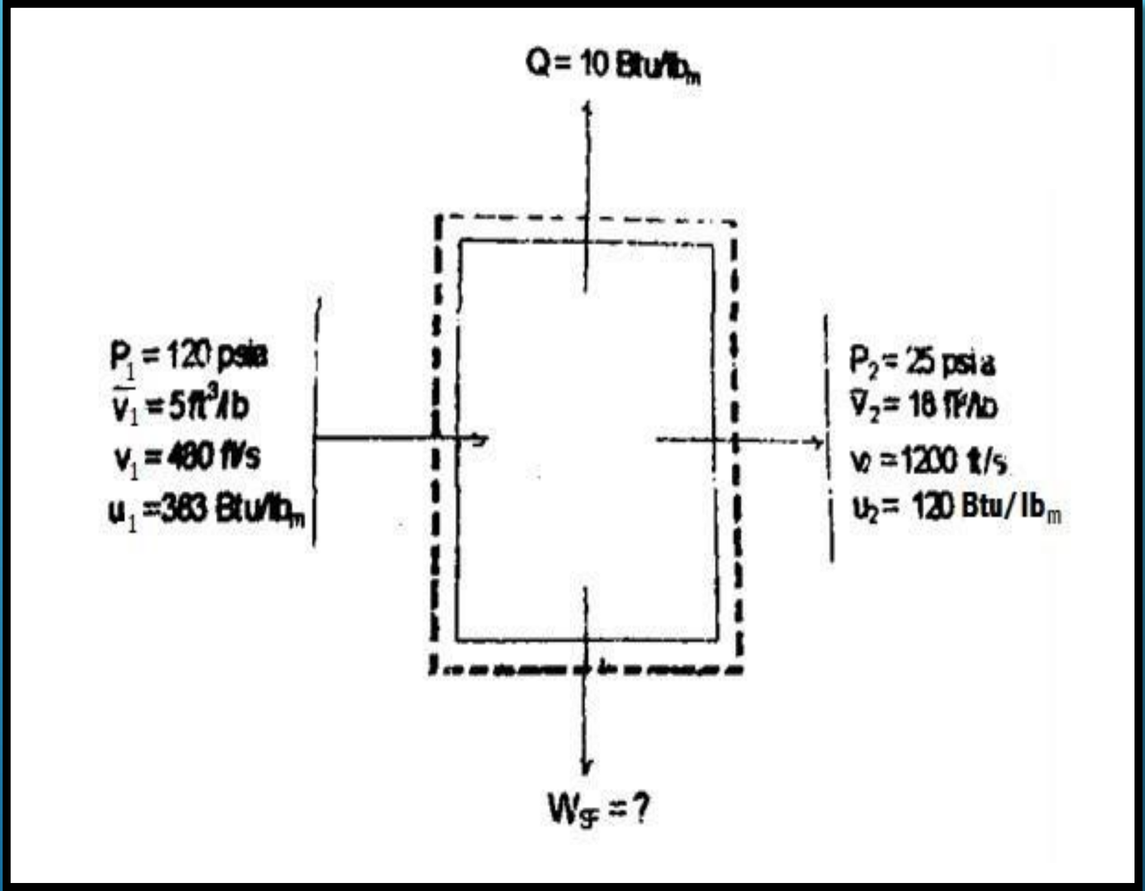
$$\boxed{Q = T\,dS}$$

$$\boxed{WSF = -V\,dP}$$

Example 1:

A fluid enters an apparatus at 480 ft/sec, initially, the pressure of the fluid is 120 psi_a, the specific volume of 5 ft^3/lb and the internal energy is 383 Btu/lb_m. The fluid leaves the apparatus at 25 psi_a, specific volume of 18 ft^3/lb_m, an exit velocity of 1200 ft/s and internal energy of 120 Btu/lb_m. The heat radiation loss is 10 Btu/lb_m. Determine work steady flow, W_{SF}.

Solution


Q= 10 Btu/lb$_m$
P$_1$ = 120 psia
$\bar{v}_1$ = 5ft^3/lb
v$_1$ = 480 ft/s
u$_1$ =363 Btu/lb$_m$
P$_2$ = 25 psia
$\bar{v}_2$ = 18 ft^3/lb
v$_2$ =1200 ft/s
u$_2$ = 120 Btu/lb$_m$
W$_{SF}$ = ?

Applying the First Law of Thermodynamics;

$$[E_{IN} = E_{OUT}]$$

$$PE_1 + KE_1 + U_1 + W_{f_1} + Q = W_{SF} + PE_2 + KE_2 + U_2 + W_{f_2}$$

$$Q = W_{SF} + \Delta PE + \Delta KE + \Delta U + \Delta W_f; \qquad \Delta PE \approx 0$$

For ΔKE;

$$\Delta KE = \frac{1}{2}\frac{m}{g_c}(v_2{}^2 - v_1{}^2)$$

$$\frac{\Delta KE}{m} = \frac{1}{2}\frac{(1200^2 - 480^2)\frac{ft^2}{sec^2}}{\left(32.2\,\frac{lb_m - ft}{lb_f - sec^2}\right)} = 18782.6087\ \frac{ft - lb_f}{lb_m}$$

$\text{Note: } 1\ Btu = 778.169\ ft - lb_f$

$$\frac{\Delta KE}{m} = 24.1369\ \frac{Btu}{lb_m}$$

For ΔW_f;

$$\Delta W_f = (P_2V_2 - P_1V_1) = m(P_2\bar{v}_2 - P_1\bar{v}_1)$$

$$\frac{\Delta W_f}{m} = (P_2\bar{v}_2 - P_1\bar{v}_1)$$

$$\frac{\Delta W_f}{m} = \left[\left(25\,\frac{lb_f}{in^2}\right)\left(18\,\frac{ft^3}{lb_m}\right) - \right.$$

For ΔU;

$$\Delta U = m(u_2 - u_1)$$

$$\frac{\Delta U}{m} = (u_2 - u_1)$$

$$\frac{\Delta U}{m} = (120 - 383)\frac{\text{Btu}}{\text{lb}_m} = -263\ \frac{\text{Btu}}{\text{lb}_m}$$

Substituting values;

$$-10\,\frac{\mathrm{Btu}}{\mathrm{lb_m}} = \mathrm{W_{SF}} + 24.1369\,\frac{\mathrm{Btu}}{\mathrm{lb_m}} - 263\,\frac{\mathrm{Btu}}{\mathrm{lb_m}} - 27.7575\,\frac{\mathrm{Btu}}{\mathrm{lb_m}}$$

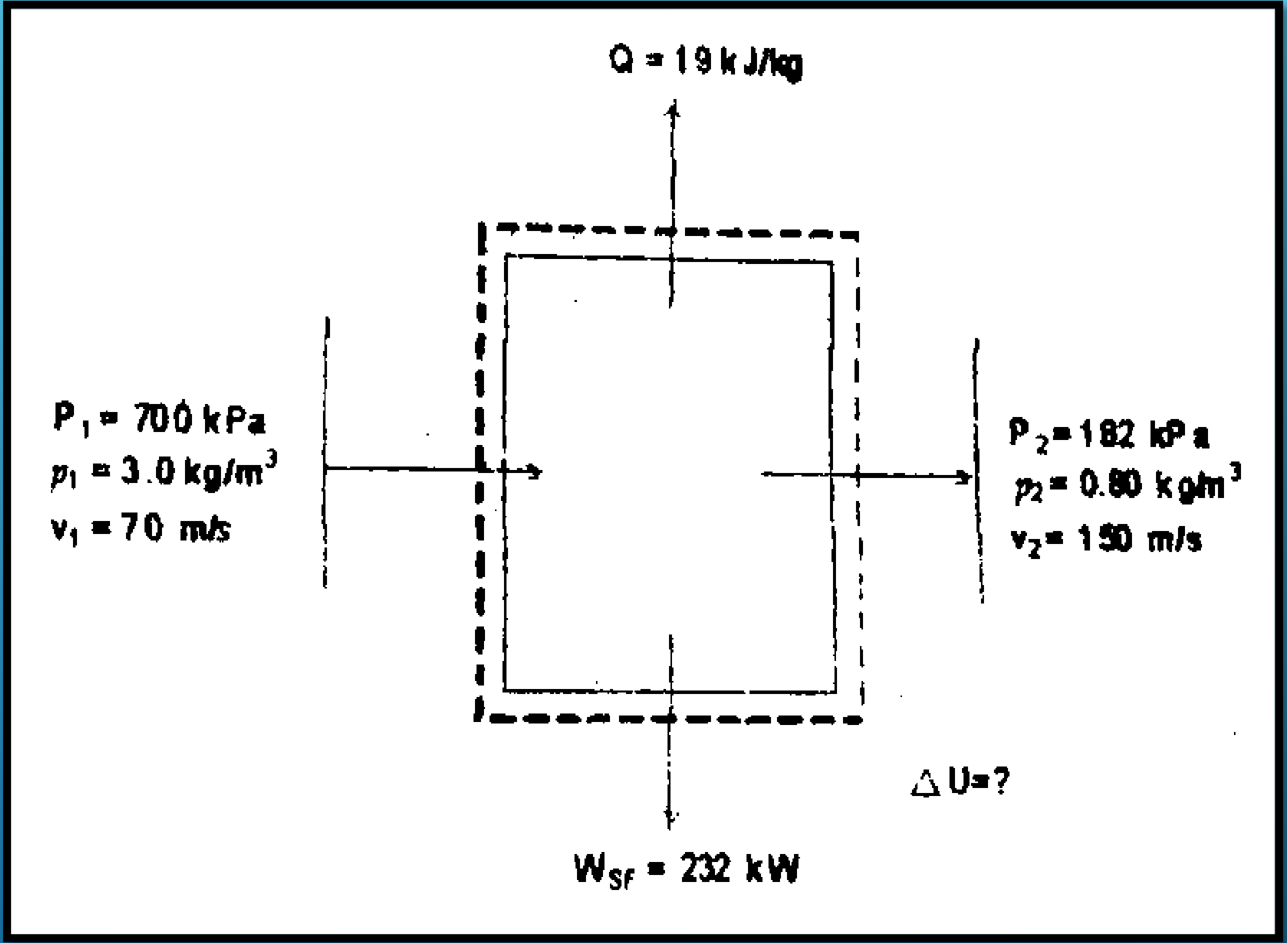
$$\mathbf{W_{SF} = 256.6206\ \frac{Btu}{lb_m}}$$

Work is done by the system

Example

A 4 kg/s of fluid enters a device with an initial pressure of 700 kPa, initial velocity of 70 m/s and the fluid initial fluid density of 3.0 kg/m^3. The fluid leaves the device at 182 kPa, 150 m/s and 0.80 kg/m^3. The heat loss from the device is 19 kJ/kg and the work done by the fluid is 232 kW. Determine the change in internal energy, in kJ/kg.

Solution


Q = 19 kJ/kg
P_1 = 700 kPa
ρ_1 = 3.0 kg/m^3
v_1 = 70 m/s
P_2 = 182 kPa
ρ_2 = 0.80 kg/m^3
v_2 = 150 m/s
ΔU=?
W_{SF} = 232 kW

Applying the First Law of Thermodynamics;

$$[E_{IN} = E_{OUT}]$$

$$PE_1 + KE_1 + U_1 + W_{f_1} = Q + W_{SF} + PE_2 + KE_2 + U_2 + W_{f_2}$$

$$-Q = W_{SF} + \Delta PE + \Delta KE + \Delta U + \Delta W_f; \qquad \Delta PE \approx 0$$

For ΔKE;

$$\Delta KE = \frac{1}{2}\frac{m}{g_c}\left({v_2}^2 - {v_1}^2\right)$$

$$\frac{\Delta KE}{m} = \frac{1}{2}\frac{\left(150^2-70^2\right)\frac{m^2}{s^2}}{\left(1\,\frac{kg-m}{N-s^2}\right)\left(\frac{1000\ N}{1\ kN}\right)} = 8.8\ \frac{kJ}{kg}$$

For ΔW_f;

$$\Delta W_f = (P_2V_2 - P_1V_1) = m(P_2\bar{v}_2 - P_1\bar{v}_1);\ \bar{v} = \frac{1}{\rho}$$

$$\frac{\Delta W_f}{m} = \left(P_2\frac{1}{\rho_2} - P_1\frac{1}{\rho_1}\right)$$

$$\frac{\Delta W_f}{m} = \left[(182\ \text{kPa})\frac{1}{0.80\ \frac{\text{kg}}{\text{m}^3}} - (700\ \text{kPa})\frac{1}{3.0\ \frac{\text{kg}}{\text{m}^3}}\right]$$

$$\frac{\Delta W_f}{m} = -5.8333\ \frac{\text{kJ}}{\text{kg}}$$

Substituting values;

$$-19\,\frac{\text{kJ}}{\text{kg}}=\left(232\ \frac{\text{kJ}}{\text{s}}\right)\left(\frac{1}{4}\ \frac{\text{s}}{\text{kg}}\right)+8.8\ \frac{\text{kJ}}{\text{kg}}+\Delta\text{U}-5.8333\ \frac{\text{kJ}}{\text{kg}}$$

$$\mathbf{\Delta U=-79.9667\ \frac{kJ}{kg}}$$

There is a decrease in internal energy

First Law in a Closed or Non-Flow System:

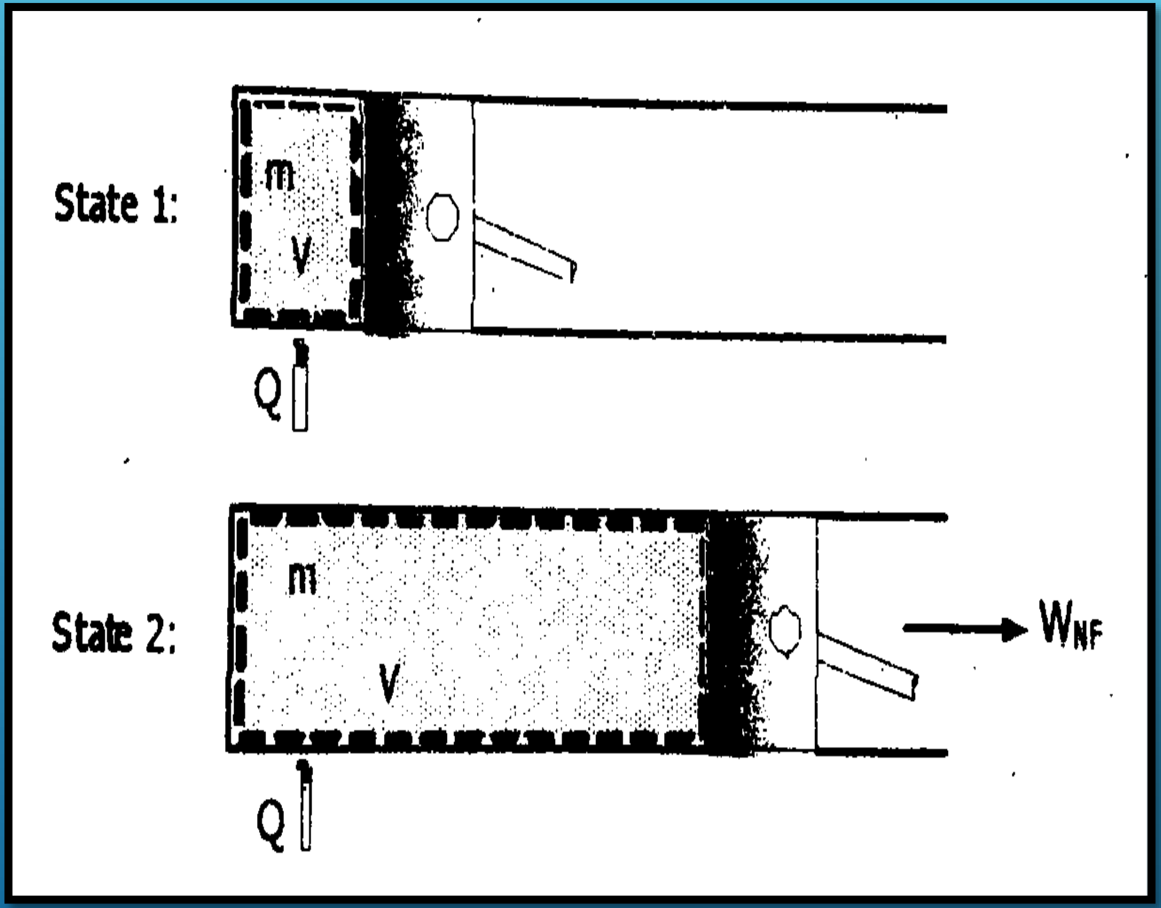


FIGURE: Energy balance in a close or non-flow thermodynamic system

$$[E_{IN} = E_{OUT}]$$

$$\begin{bmatrix} \text{Initial energy} & & \text{Initial energy} \\ \text{stored within} & + & \text{entering the} \\ \text{the system} & & \text{system} \end{bmatrix} = \begin{bmatrix} \text{Final energy} & & \text{Final energy} \\ \text{stored within} & + & \text{entering the} \\ \text{the system} & & \text{system} \end{bmatrix}$$

$$PE_1 + KE_1 + U_1 + W_{f_1} + Q = W_{NF} + PE_2 + KE_2 + U_2$$

$$Q = W_{NF} + \Delta PE + \Delta KE + \Delta U$$

When:

$$\Delta PE \approx 0;\ Z_1 \approx Z_2$$

$$\Delta KE \approx 0;\ V_1 \approx V_2$$

And:

$$\boxed{Q = W_{NF} + \Delta U}$$ Non-Flow Energy Equation (NFEE)

In differential form:

$$dQ = dW_{NF} + dU$$

General Formula:

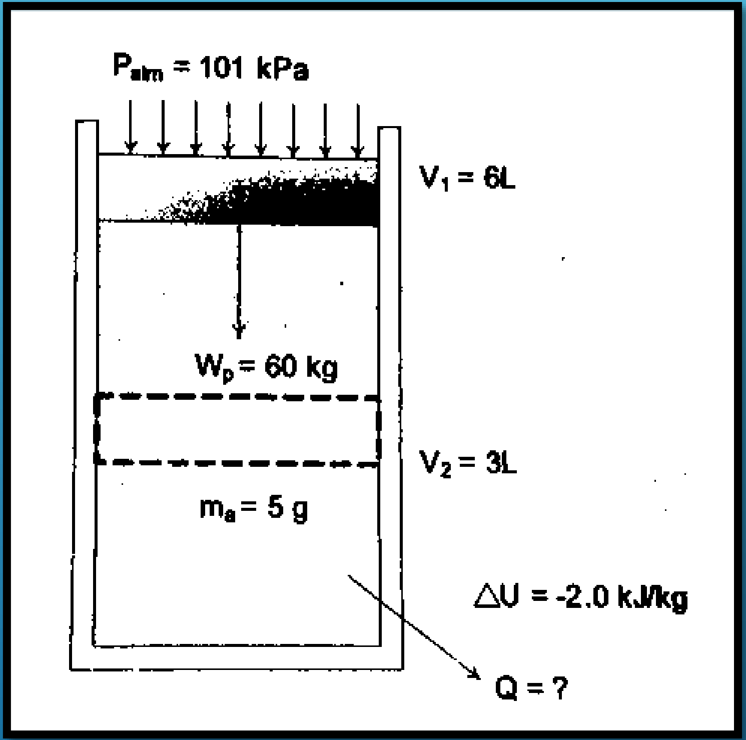
$$\boxed{Q = T\,dS}$$

$$\boxed{WNF = P\,dV}$$

Example

A vertical piston cylinder arrangement shown below with a piston mass of 60 kg with a face area of 150 cm^2, contains 5 grams of air. The initial volume occupied by the air is 6 L. A decrease in internal energy amounting to 2.0 kJ occurs because of the temperature difference between the surroundings and volume inside the cylinder that caused the volume to decrease by 3 L. The atmospheric pressure at the top of the piston is 101 kPa. Neglect the friction effects between the surface of the piston and the cylinder. Determine the change in internal energy of air, in kJ/kg.

Solution



We will first assume that the direction of the heat flow is going out of the system, if our final answer is positive, it simply means that our assumption is correct.

Applying the First Law of Thermodynamics;

$$[E_{IN} = E_{OUT}]$$

$$\begin{bmatrix} \text{Initial energy} & & \text{Initial energy} \\ \text{stored within} & + & \text{entering the} \\ \text{the system} & & \text{system} \end{bmatrix} = \begin{bmatrix} \text{Final energy} & & \text{Final energy} \\ \text{stored within} & + & \text{entering the} \\ \text{the system} & & \text{system} \end{bmatrix}$$

$$PE_1 + KE_1 + U_1 = Q + W_{NF} + PE_2 + KE_2 + U_2$$

$$0 = Q + W_{NF} + \Delta PE + \Delta KE + \Delta U; \qquad \Delta PE \approx 0 \text{ and } \Delta KE \approx 0$$

$$-Q = W_{NF} + \Delta U$$

For W_{NF};

$$W_{NF} = P\int_1^2 dV = P(V_2 - V_1)$$

$$P_{Piston} = \frac{F}{A} = \frac{m}{A}\left(\frac{g_o}{g_c}\right)$$

$$P_{Piston} = \frac{(60\ kg)\left(\dfrac{9.81\ \frac{m}{s^2}}{1000\ \frac{kg-m}{kN-s^2}}\right)}{0.015\ m^2} = 39.24\ kPa$$

$$W_{NF} = (101 + 39.24)\ kPa\ (0.003 - 0.006)m^3$$

$$W_{NF} = -0.4207\ kJ$$

Substituting values;

$$-Q = -0.4207\ \text{kJ} - 2.0\ \text{kJ}$$
$$Q = 2.4207\ \text{kJ}$$

Or, in terms of kJ/kg;

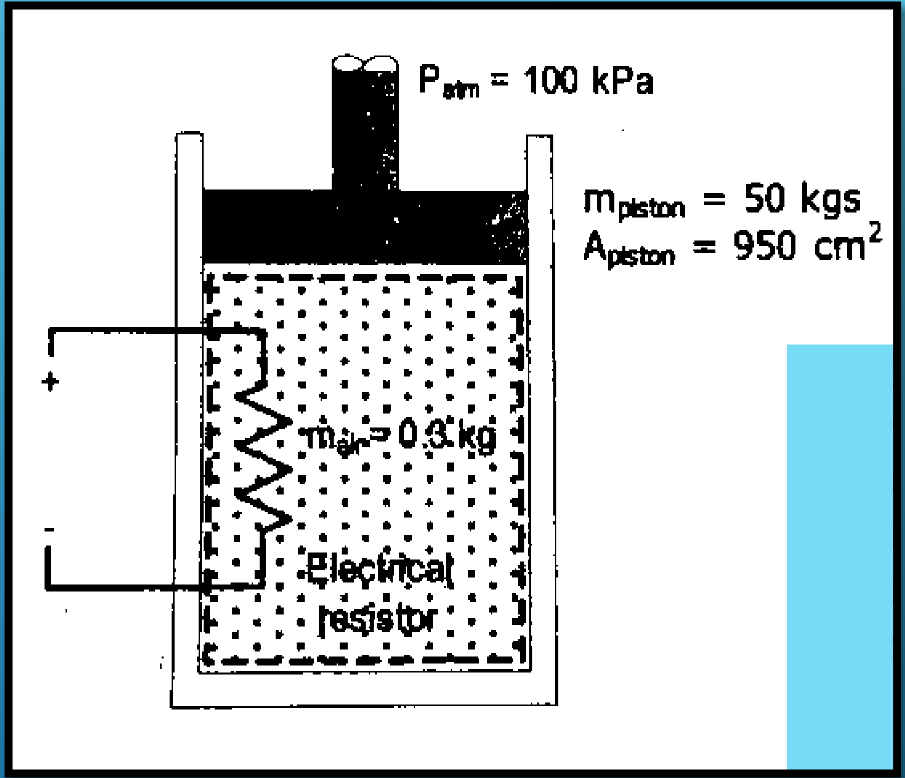
$$Q = \frac{2.4207\ \text{kJ}}{0.005\ \text{kg}}$$
$$\mathbf{Q = 484.14\ \frac{kJ}{kg}}$$

Since our final answer is positive, therefore our first assumption that heat is going out of the system is correct.

Example

A piston cylinder assembly as shown in the figure below contains 0.3 kg of air and is fitted with electrical resistor. The mass of the piston is 50 kg and with a face area of 950 cm^2. The heat transfer produced by the electric current passes through the resistor is 19 kJ that caused the volume to increase by 45 L, while maintaining a constant pressure. At initial and final state, the air and the piston are at rest. Neglect the friction effects between the surface of the piston and the cylinder and take the local acceleration of gravity as g_o=9.81 m/s^2. Determine the change in internal energy, in kJ.

Solution


P_{atm} = 100 kPa
m_{piston} = 50 kgs
A_{piston} = 950 cm^2
+
-
m_{air} = 0.3 kg
Electrical resistor

Applying the First Law of Thermodynamics;

$$[\mathrm{E_{IN}} = \mathrm{E_{OUT}}]$$

$$\begin{bmatrix} \text{Initial energy} & & \text{Initial energy} \\ \text{stored within} & + & \text{entering the} \\ \text{the system} & & \text{system} \end{bmatrix} = \begin{bmatrix} \text{Final energy} & & \text{Final energy} \\ \text{stored within} & + & \text{entering the} \\ \text{the system} & & \text{system} \end{bmatrix}$$

$$\mathrm{PE_1 + KE_1 + U_1 + Q = W_{NF} + PE_2 + KE_2 + U_2}$$

$$\mathrm{Q = W_{NF} + \Delta PE + \Delta KE + \Delta U}; \qquad \mathrm{\Delta PE \approx 0 \text{ and } \Delta KE \approx 0}$$

$$\mathrm{Q = W_{NF} + \Delta U}$$

For W_{NF};

$$W_{NF} = P\int_1^2 dV = P(V_2 - V_1)$$

Upward pressure exerted by air:

$$P = P_{atm} + P_{piston} = P_{atm} + \frac{F_{piston}}{A_{piston}}$$

$$P = 100\ \text{kPa} + \frac{50\ \text{kg}}{950\ \text{cm}^2\left(\frac{1\ \text{m}}{100\ \text{cm}}\right)^2}\left(\frac{9.81\ \frac{\text{m}}{\text{s}^2}}{1000\ \frac{\text{kg}-\text{m}}{\text{kN}-\text{s}^2}}\right)$$

$$P = 105.1632\ \text{kPa}$$

$$W_{NF} = \left(105.1632\ \frac{kN}{m^2}\right)(0.045\ m^3)$$

$$W_{NF} = 4.7323\ kJ$$

Substituting values;

$$Q = W_{NF} + \Delta U$$

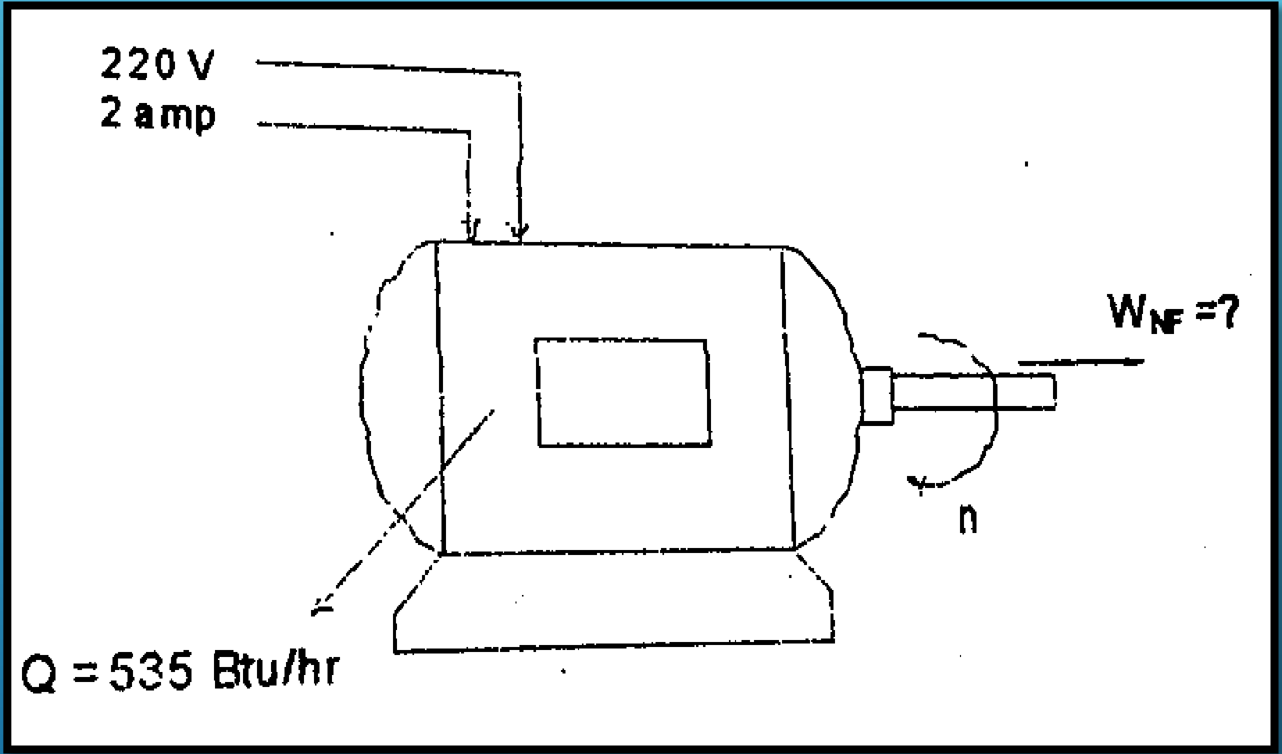
$$19\ kJ = 4.7323\ kJ + \Delta U$$

$$\mathbf{\Delta U = 14.2677\ kJ}$$

Example

An electric motor shown in the figure draws 2 amps at 220 V to produce a power output. The rate of heat loss due to radiation is 535 Btu/hr and the temperature of the surface of the motor is measured to be 130°F. Determine the power developed by the motor in horsepower and the rate of change in entropy in Btu/hr-°R.

Solution



Applying the First Law of Thermodynamics;

$$[E_{IN} = E_{OUT}]$$

$$W_{ELEC} = Q + W_{NF}$$

For W_{ELEC};

$$W_{ELEC} = (2\ \text{amp})(220\ \text{V}) = 440\ \text{W}$$

$$\text{Note: } 1\ \text{W} = 3.413\ \text{Btu/hr}$$

$$W_{ELEC} = 1501.72\ \frac{\text{Btu}}{\text{hr}}$$

Substituting;

$$1501.72\ \frac{\text{Btu}}{\text{hr}} = 535\ \frac{\text{Btu}}{\text{hr}} + \text{W}_{\text{NF}}$$

$$\text{W}_{\text{NF}} = 966.72\ \frac{\text{Btu}}{\text{hr}}$$

$$\text{Note: } 1\ \text{hp} = 2544.5\ \text{Btu/hr}$$

$$\mathbf{W_{NF} = 0.3799\ hp}$$

Solving for ΔS;

From: $Q = T\int dS$

$$\int_1^2 dS = (S_2 - S_1) = \Delta S = \frac{Q}{T}$$

$$\Delta S = \frac{-535\ \frac{\text{Btu}}{\text{hr}}}{(130 + 460)°\text{R}}$$

$$\boldsymbol{\Delta S = -0.9068\ \frac{\textbf{Btu}}{\textbf{hr} - °\textbf{R}}}$$

Example

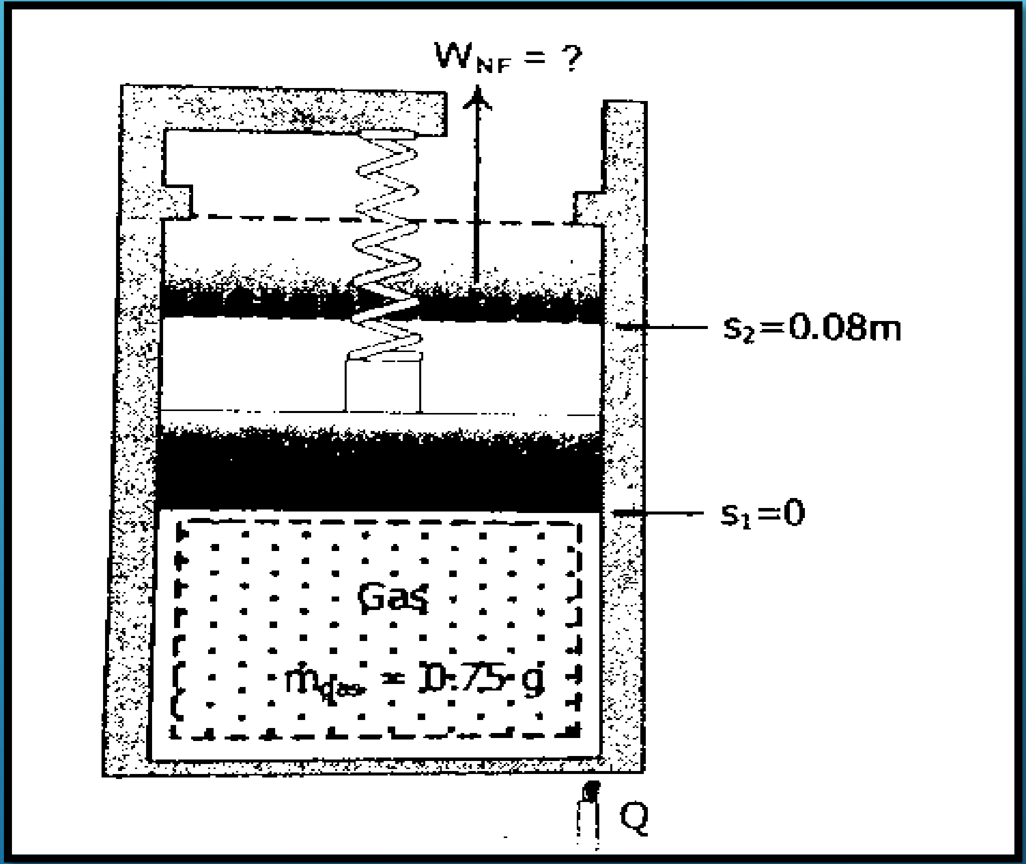
A 8 kg gas contained in a vertical piston cylinder assembly is shown in the figure below. The area and the mass of the piston are 300 cm^2 and 15 kg, respectively. A spring is loaded in the piston, which the force exerted varies linearly with the displacement, s. At initial position, the piston face is at s=0, the spring exerts no force. Heat is added to the air causing the gas to expand until the piston reached the stops at s=0.08 m, and the heat transfer ceases. The atmosphere pressure is 1 bar, the observed gravitational acceleration is g_o=9.81 m/s^2, consider the spring constant, k, to be 8500 N/m and neglect friction between the piston and the cylinder. Determine:

(a) The initial pressure of the gas, kPa

(b) The work done by the gas on the piston in J

(c) The heat transfer in J, when the specific internal energies of the gas at the initial and final states are 210 and 335 kJ/kg, respectively.

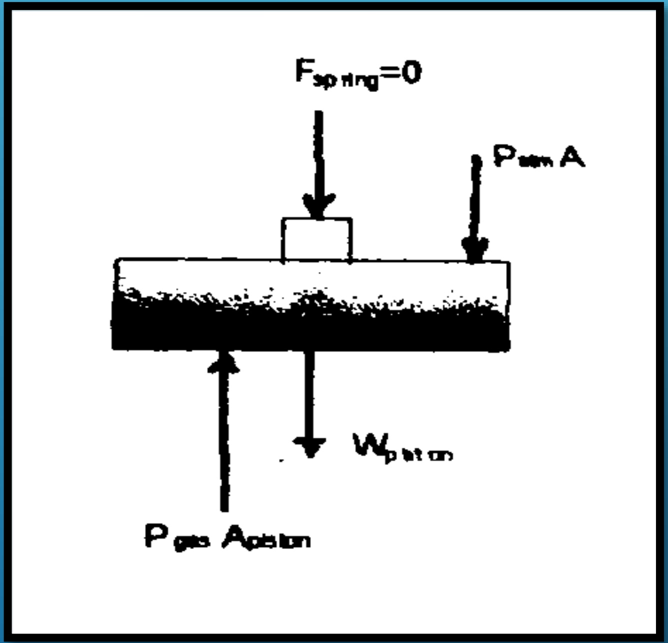
Solution



Solving for the initial pressure of the gas:

Initially the spring does not exert any force on the piston.

Initial Free Body Diagram of the piston, s=0:



$$\left[\sum F_y = 0\right] \uparrow +$$

$$P_{gas}A_{piston} - W_{piston} - P_{atm}A_{piston} = 0$$

$$P_{gas} = \frac{m_{piston}}{A_{piston}}\left(\frac{g_o}{g_c}\right) + P_{atm} = \frac{8\ \text{kg}}{0.03\ \text{m}^2}\left(\frac{9.81\ \frac{\text{m}}{\text{s}^2}}{1\ \frac{\text{kg}-\text{m}}{\text{N}-\text{s}^2}}\right) + 100000\ \text{Pa}$$

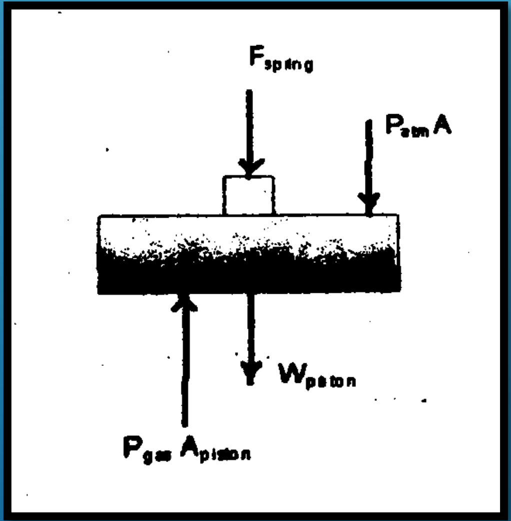
$$P_{gas} = 102{,}616\ \text{Pa}$$

The pressure exerted by the gas initially:

$$\mathbf{P_{gas} = 102.616\ kPa}$$

Solving for the work done by the gas on the piston:

The force exerted by the spring now acts on the piston as it moves from s=0 to s=0.08 m:



$$\left[\sum F_y = 0\right] \uparrow +$$

$$P_{gas}A_{piston} - W_{piston} - P_{atm}A_{piston} - F_{spring} = 0$$

$$P_{gas}A_{piston} = W_{piston} + P_{atm}A_{piston} + ks$$

The work done by the gas on the piston:

$$W_{NF} = \int_1^2 P_{gas} dV = \int_1^2 P_{gas} A_{piston} ds$$

$$W_{NF} = \int_{s_1}^{s_2} \left(W_{piston} + P_{atm} A_{piston} + ks\right) ds$$

$$W_{NF} = \left[\left(W_{piston} + P_{atm} A_{piston}\right) s + k\frac{s^2}{2}\right]_0^{0.08}$$

$$W_{NF} = \left[8\text{ kg}\left(\frac{9.81\,\frac{\text{m}}{\text{s}^2}}{1\,\frac{\text{kg}-\text{m}}{\text{N}-\text{s}^2}}\right) + (100,000\text{ Pa})(0.03\text{ m}^2)\right](0.08\text{ m}) + \left(8500\,\frac{\text{N}}{\text{m}}\right)\frac{(0.08\text{ m})^2}{2}$$

$$\mathbf{W_{NF} = 273.4784\ J}$$

Solving for the heat transfer, using NFEE:

$$Q = W_{NF} + \Delta U$$

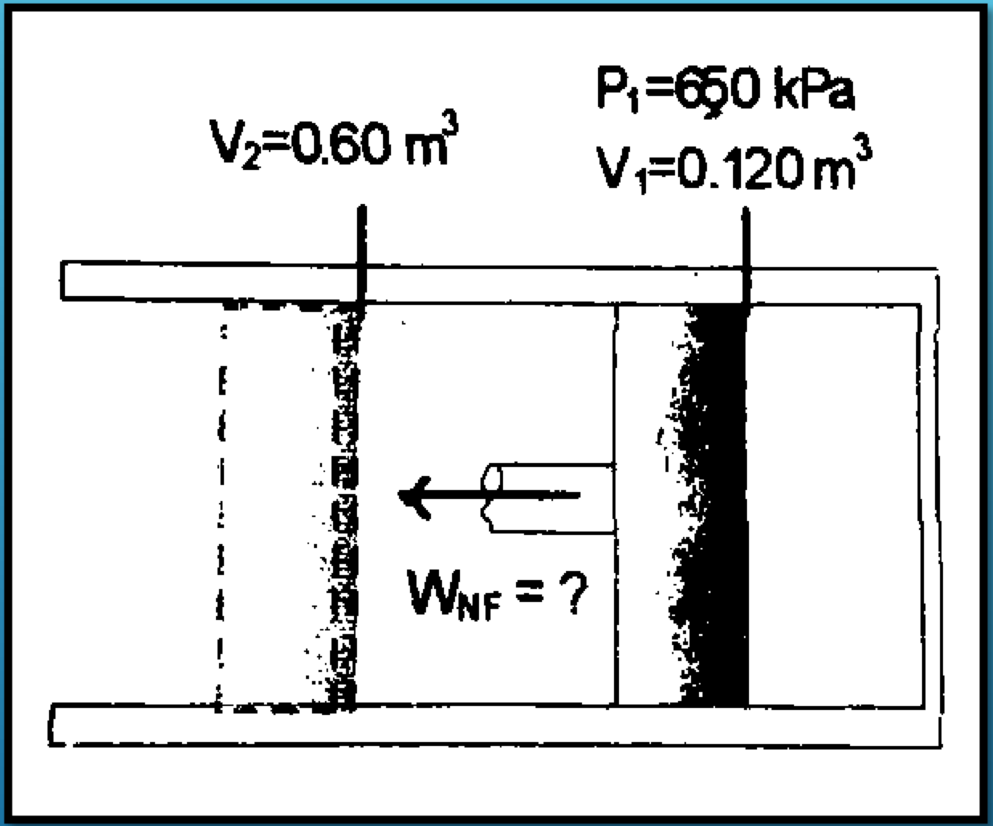
$$Q = \ 273.4784\ J + (0.008\ g)(335 - 210)\frac{J}{g}$$

$$\mathbf{Q = 274.4784\ J}$$

Example

A gas contained in a piston-cylinder. The gas expands slowly from an initial pressure and volume of 650 kPa and 0.120 m^3, respectively, to a final volume of 0.60 m^3. Determine the work done, in kJ, if the quantity PV remains constant, where V is in m^3 and P is in kPa. Also determine the final pressure of the gas.

Solution



$$W_{NF} = \int_{1}^{2} PdV$$

$$PV = C = P_1V_1 = P_2V_2; \quad P = \frac{C}{V}$$

Where: $C = \text{constant}$

$$W_{NF} = C\int_{V_1}^{V_2} \frac{dV}{V} = C\ln\left(\frac{V_2}{V_1}\right) = P_1V_1\ln\left(\frac{V_2}{V_1}\right)$$

$$W_{NF} = (650\ \text{kPa})(0.120\ \text{m}^3)\ln\left(\frac{0.60\ \text{m}^3}{0.120\ \text{m}^3}\right)$$

$$\mathbf{W_{NF} = 125.5361\ kJ}$$

Solving for the final pressure of the gas:

$$\mathrm{P_1V_1 = P_2V_2}$$

$$(650\ \mathrm{kPa})(0.120\ \mathrm{m^3}) = \mathrm{P_2}(0.60\ \mathrm{m^3})$$

$$\mathbf{P_2 = 130\ kPa}$$

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